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A FIRST LOOK AT THE EFFECT OF SEVERE RAINFALL UPON AN AIRCRAFT

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INTRODUCTION

In recent years the effect of wind shear on aircraft, especially that shear associated with thunderstorms, has received considerable attention. Accidents such as the Eastern Flight 066 at Kennedy Airport precipitated an intensive investigation of the types and magnitude of shear associated with strong convective cells embedded within a thunderstorm. The National Transportation Safety Board's reconstruction of the flight recorder data from this accident determined the magnitude of this wind shear, assuming that the shear was the only external factor affecting the aircraft. Extraordinarily large shear values were calculated. In the reconstruction, however, no allowance for performance degradation due to the heavy rain cell experienced by the Eastern Flight 066 was taken into account. Thus, it appears possible that the derived wind shears were too large because the performance degradation resulting from the extremely heavy downpour was ignored.

An aircraft penetrating heavy rain can be affected aerodynamically in at least four ways: (a) raindrops striking the fuselage and wings of the aircraft impart a downward momentum to the aircraft; (b) increased aircraft drag results from the aircraft striking the raindrops head on; (c) at any instant of time the aircraft will contain a thin layer of water over most of its surfaces which will give additional mass to the aircraft; and (d) the water on the airfoil will result in a roughened airfoil surface that could produce significant aerodynamic penalties.

Though some of the above factors may be small or even negligible, all contribute negative performance and the sum total of all factors may produce a substantial penalty to an aircraft in a landing configuration.

An order of magnitude calculation has been made for the penalty associated with the factors (a), (b) and (c). The roughness factor requires detailed modeling and boundary layer calculations and will be studied using the "Aerodynamic Effects of Frost Model" (AEFM). Preliminary study of the impingement efficiency needed for the AEFM has been completed for various size distributions of raindrops. The following sections describe the results achieved to date on each of the penalty factors and indicates which factors are most likely to cause significant performance degradation.

SIZE DISTRIBUTION OF WATER DROPLETS

To analyze the effect of heavy rain on aircraft performance, the size distribution of water droplets under different rainfall rates must first be established. The classical paper on the size distribution of rain drops is that of Marshall and Palmer (1948). According to their results the size distribution can be approximated by the exponential function

$$\frac{dN(D)}{dD} = N_o e^{-\lambda D} \tag{1}$$

where

λ	equals $41R^{-0.21}$;
R	is the rainfall rate in mm/hr;
N_o	is the empirical constant (0.08);
D	is the drop diameter; and
N(D)	is the number of drops within diameter range dD.

The drop distribution for several different rainfall rates is presented in Figure 1.

The distribution was originally derived from extratropical rainfall but Merceret (1975) found it valid for tropical showers as well. Additional investigators have adjusted the original coefficients, but Equation 1 remains sufficiently valid for studying heavy rain effects on aircraft.

The terminal velocity of raindrops of drop diameter, D, has been established by Markowitz (1976) as

$$V(D) = 9.58\left\{1 - \exp\left[-\left(\frac{D}{1.77}\right)^{1.147}\right]\right\} \tag{2}$$

where V(D) is the terminal velocity. A correction for terminal velocity as a function of density is given by Markowitz as

$$V(D) = V_o(D)\left(\frac{\rho_o}{\rho}\right)^{0.4} \tag{3}$$

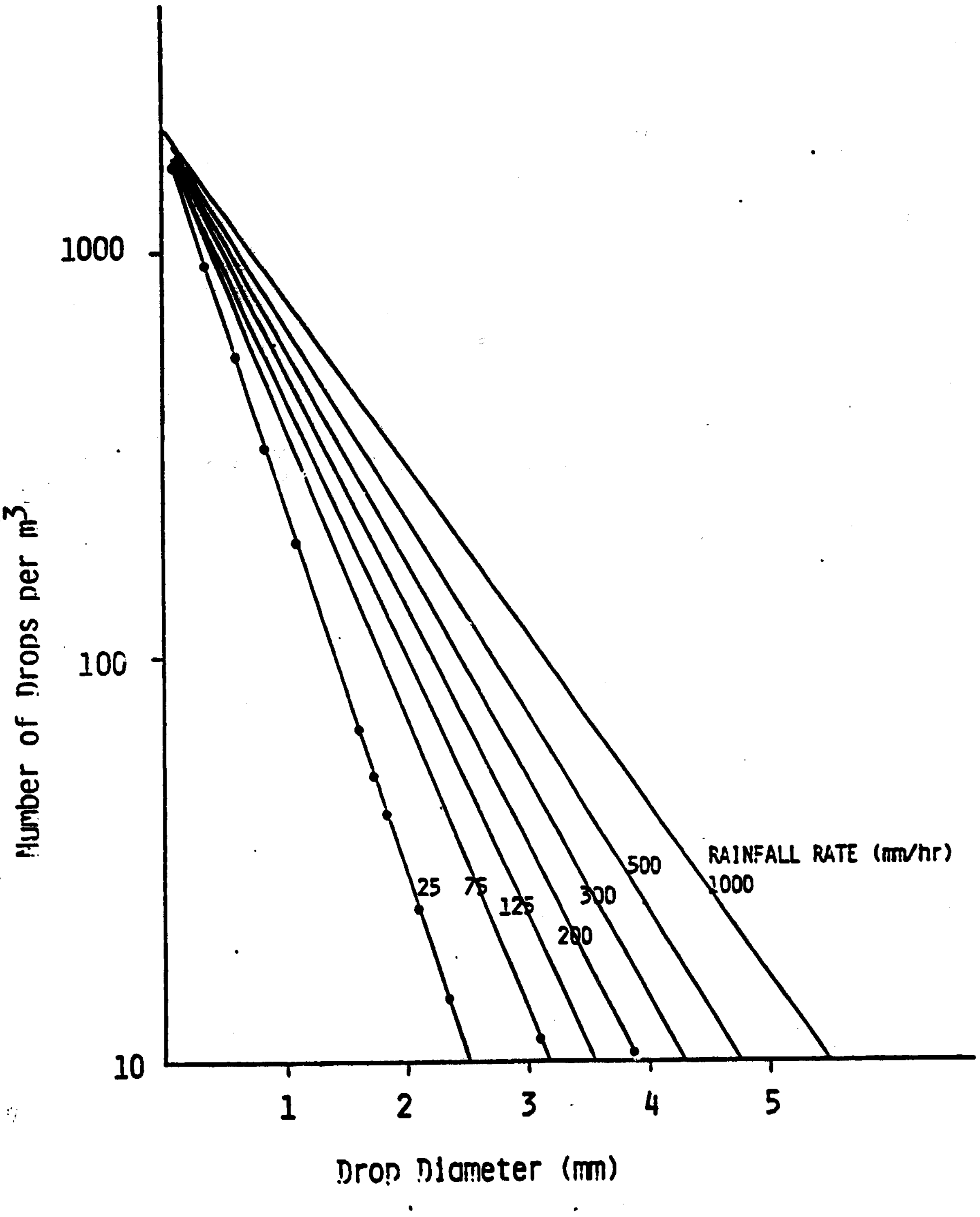


Figure 1. Drop-Size Distributions for Different Rain-Rates

where ρ is the density at level of interest;
ρ_o is the surface density;
$V_o(D)$ is the surface terminal velocity; and
$V(D)$ is the terminal velocity at level of interest.

Equation 3 allows for terminal velocity adjustment for impingement on aircraft at higher flight levels.

The percent volume contribution to the total rainfall can be calculated for each diameter increment knowing the terminal velocity of each size droplet and the number of droplets. This leads to a volume mean drop diameter.

To calculate the fraction of total volume of water striking a surface due to raindrops of diameter D, we follow Markowitz (1976). The fraction for a diameter dD is

$$M(D)dD = N(D)\frac{4}{3}\pi\left(\frac{D}{2}\right)^3 V(D)dD \Big/ \int_0^\infty N(D)\frac{4}{3}\pi\left(\frac{D}{2}\right)^3 V(D)dD \qquad (4)$$

where $M(D)$ is the percent of volume for diameter D,
$N(D)$ is the number of drops for diameter D,
$V(D)$ is the terminal velocity for D, and
D is the diameter.

N(D) is calculated from the Marshall Palmer Equation 1, while V(D) is calculated from Equation 2.

In Figure 1, drop-size distributions calculated from Equation 1 can be seen. Each line represents the distribution corresponding to the rainfall rate listed next to it. Terminal drop velocities by radius from Equation 2 are listed in Table 1. Finally, Figure 2 shows the percentage volume contributions for three rainfall rates by drop diameter. The volume mean diameter for a given rainfall rate is easily obtained from Figure 2.

A scheme for classifying rainfall rates as moderate, severe, or incredible has been based upon several reports found in the literature. Jones and Sims (1978) report frequencies

TABLE 1

TERMINAL VELOCITIES

Drop Radius (mm)	Terminal Velocity (m/sec)
0.10	0.75
0.20	1.59
0.30	2.41
0.40	3.17
0.50	3.88
0.60	4.53
0.70	5.12
0.80	5.65
0.90	6.12
1.00	6.55
1.10	6.93
1.20	7.26
1.30	7.55
1.40	7.82
1.50	8.05
1.60	8.25
1.70	8.42
1.80	8.58
1.90	8.71
2.00	8.83
2.10	8.93
2.20	9.02
2.30	9.10
2.40	9.17
2.50	9.22
2.60	9.27
2.70	9.32
2.80	9.35
2.90	9.39
3.00	9.41
3.10	9.44
3.20	9.46
3.30	9.48
3.40	9.49
3.50	9.50
3.60	9.52
3.70	9.52
3.80	9.53
3.90	9.54
4.00	9.55
4.10	9.55
4.20	9.56
4.30	9.56
4.40	9.56
4.50	9.56
4.60	9.57
4.70	9.57
4.80	9.57
4.90	9.57
5.00	9.57

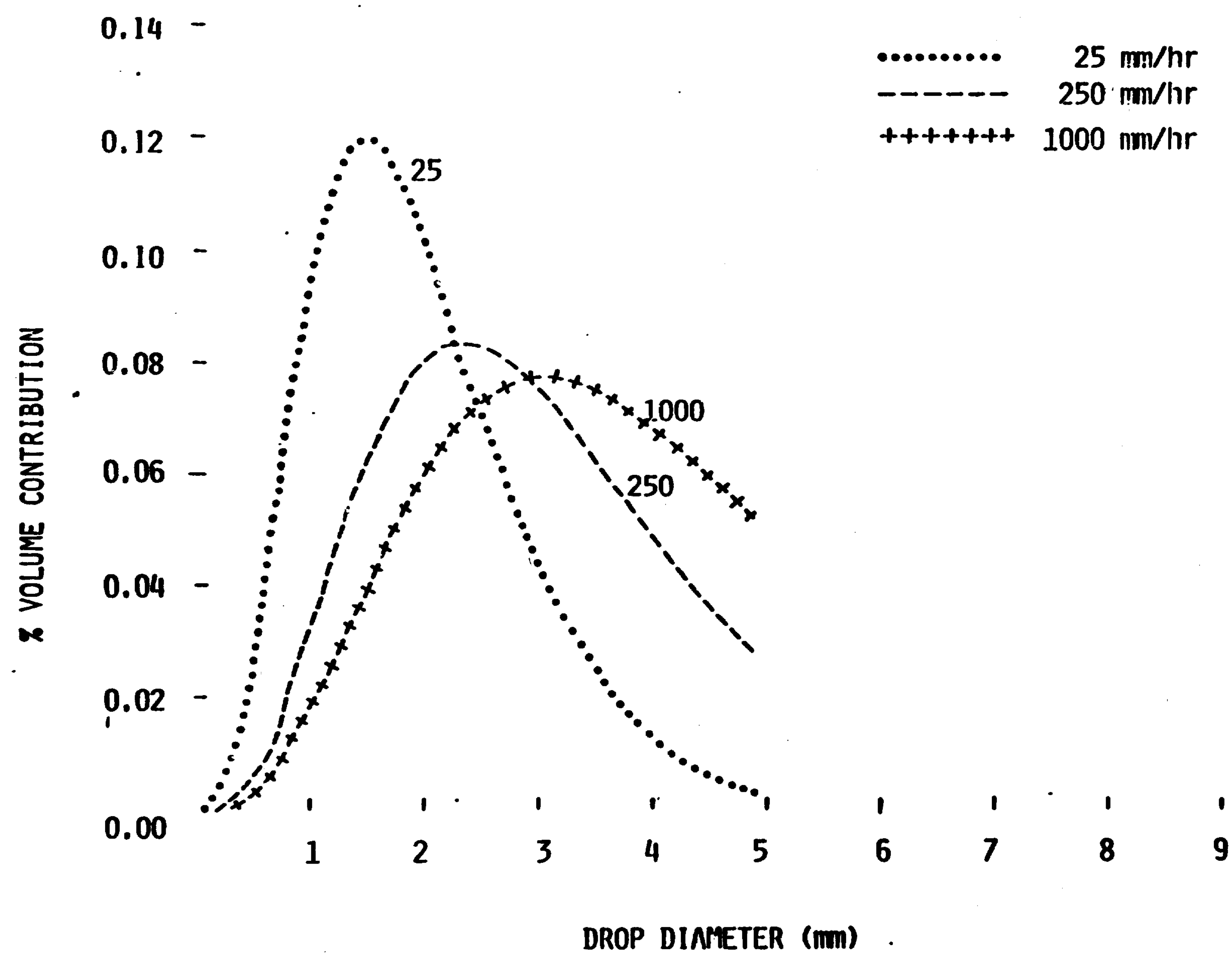
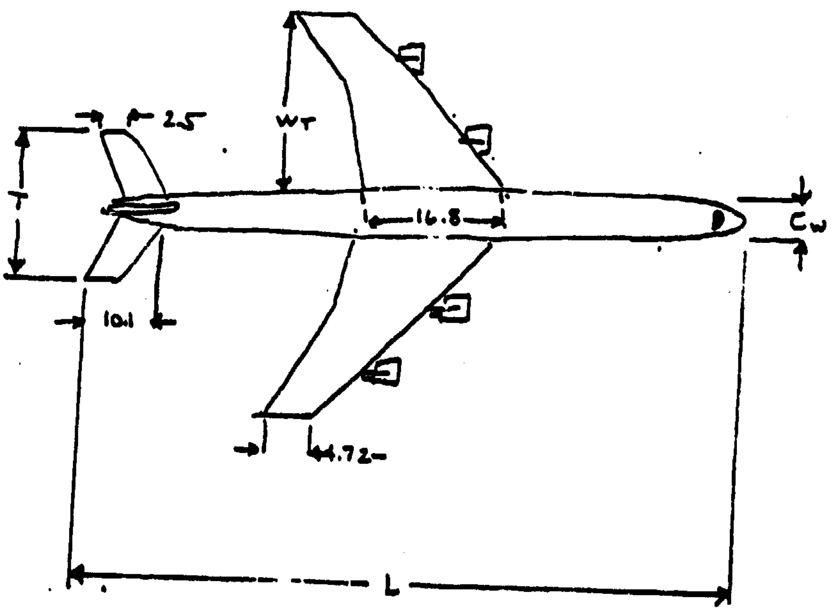


Figure 2. Percent Volume Contribution of Three Rainfall Rates (25 mm/hr^{-1}, 250 mm/hr^{-1}, 1000 mm/hr^{-1}) by Drop Diameter. Volume mean diameters increase for higher rainfall rates.

of one and four minute rainfall rates for a variety of stations. According to this report a rainfall rate above 300 mm/hr for a one-minute period was found to be unusual. Hershfield (1972) supports this contention. Unfortunately, information about rates for periods shorter than one minute are unavailable. Bodtmann and Ruthoff (1976) determined rain rate distributions for 20 cities in the United States. Their report shows for each city the number of minutes each year that a specified rain rate is exceeded. Blanchard and Spencer (1970) reported some Florida observations of rainfall rates up to 722 mm/hr. Jones and Sims (1975) also reported a 300-mm/hr rainfall rate at Naha over a four-minute period. It is conceivable that instantaneous rates are two to three times the maximum one-minute rates. A rainfall rate of 1000 mm/hr is thus possible. Such a rate will be classified as incredible, 100 mm/hr as severe, and 25 mm/hr as heavy.

WEIGHT OF WATER ON AN AIRCRAFT

Assuming an incredible rainfall rate of 1000 mm/hr or about 40 in./hr, the weight of the water on the top surface of a 747 aircraft has been calculated as follows. The top surface area of a 747 jet is roughly approximated as:



L - 70.5 m
WT - 22.2 m
T - 22.2 m
CW - 7.6 m

NOTE: Drawing not to scale.

The approximate component areas are:

Fuselage Area	536 m^2	(70.5 m X 7.6 m)
Wing Area	478 m^2	
Tail Area	92 m^2	
Engine Area	25 m^2	
TOTAL AREA	1131 m^2	

The amount of rain intercepted per unit time has been established by a two-part calculation: (1) Assuming the rain falls with no horizontal component, the rain intercepted due to horizontal area of the plane was calculated. (2) A correction was calculated by adding an amount due to the frontal area of the plane sweeping the rain.

The mass of rain falling on horizontal area is:

$$\text{rain rate (cm/sec)} \times \text{area (cm}^2) \times \text{density (gm/cm}^3) = \text{gm/sec}$$
$$= (2.78 \times 10^{-2}\,\text{cm/sec})(1.131 \times 10^7\,\text{cm}^2)(1\,\text{gm/cm}^3)$$
$$= 3.14 \times 10^5\,\text{gm/sec}$$
$$= 314\,\text{kg/sec}$$

The mass of rain being swept by plane is approximately the volume swept by plane multiplied by the density of rain within the volume. The volume is the frontal area of the aircraft multiplied by the aircraft landing velocity (~ 65 m/sec). The frontal area of the plane is given in Table 2.

TABLE 2

APPROXIMATE FRONTAL AREA OF PLANE

Engines	21.8 m^2
Wings	41.7 m^2
Fuselage	38.2 m^2
Tail	18 m^2
TOTAL	119.7 m^2

The volume is:

$$\text{Volume} = 119.7 \times 65 = 7.78 \times 10^3\ \text{m}^3/\text{sec}.$$

The density of rain derived from the rainfall rate and the terminal velocity (Equation 3) is:

Density = $2.78 \times 10^{-5} gm/cm^3$.

The mass of rain intercepted by the aircraft is:

$$\text{Intercept Mass} = 7.78 \times 10^{9} cm^3/sec \times 2.78 \times 10^{-5} gm/cm^3$$
$$= 216 \text{ kg/sec.}$$

This yields a total of 530 kg of water intercepted by the plane every second.

To assess the amount of rain clinging to the aircraft at an instance of time, it is necessary to estimate the average residing time of a water droplet from when it impacts the aircraft to when it runs off the back of the airfoil, fuselage, tail, etc. Obviously different points of impact have different residency times, as do different size droplets. The residency time depends largely on the boundary layer velocity profile in which the droplet becomes imbedded after impact. The calculation of residency times for different size droplets and impact points is a complicated, three-dimensional, boundary layer/potential flow problem not justified in pursuing at this point of the investigation. By making rational, order of magnitude type approximations a first estimate of the amount of water on the airfoil at an instance of time can be derived as follows. At a landing speed of 65 meters/sec and a fuselage length of 70.5 meters, a free stream air particle would travel the length of the aircraft in approximately 1 second. Water droplets imbedded in the boundary layer would of course have a much slower runback velocity. Nevertheless, with incredible rainfall rates much of the impacting water droplets would be expected to splash smaller droplets out from the boundary increasing the runback velocity. Thus average residency times on the order of one to five seconds might be a reasonable estimate. Such a residency time range would correspond to a mass of water on the aircraft on the order of 530 kg to 2650 kg. For example, compared to a landing weight for a 747 aircraft of 200,000 kg the increase would be less than 1.5%. The effect of this increase in mass should be readily controllable by increased available thrust.

To further scrutinize the estimate of 530 kg to 2650 kg of water on the aircraft at an instant of time, Table 3 was generated relating the average water film thickness to the total weight of the water on the top surface of the 747 aircraft.

TABLE 3

Water Film Thickness	Approximate Total Weight
0.5 mm	550 kg
1 mm	1100 kg
2 mm	2200 kg
3 mm	3300 kg
4 mm	4400 kg
5 mm	5500 kg

Based upon intuition and observations of windshield wiper buildup and removal during heavy rain conditions water film thicknesses on the order of two to three millimeters seem reasonable. Average film thickness in excess of five millimeters (0.5 cm) would seem to be unreasonably large. Thus even with an average film thickness of three to five millimeters the resulting increase in landing weight is less than 3%--a value small enough to be compensated for by proper thrust and aerodynamic control surfaces. It therefore appears that the increased weight of the water on an aircraft while experiencing heavy rain has only a small effect on aircraft performance. Though the above analysis was performed for a 747 aircraft, it would be expected to be valid for other aircraft because of similar ratios of surface and frontal area to gross aircraft weight.

MOMENTUM OF RAINDROPS

Raindrops striking an aircraft lose momentum to the aircraft thus changing the velocity of the aircraft. The vertical component of the raindrop velocity imparts downward momentum to the aircraft which tends to make it sink. The aircraft striking raindrops head-on slows the aircraft because energy is lost by the aircraft in accelerating the water droplets to the velocity of the aircraft. The amount of energy imparted to an aircraft by striking a raindrop depends on the reflection angle of the raindrops. Collisions at oblique angles impart less energy than larger reflection angles that approach 180°. To estimate the impacted momentum for a 747 aircraft the following assumptions are made.

1. All rain impinging on the aircraft accelerates to the velocity of the aircraft.

2. All rain intercepting the path of the aircraft strikes the aircraft, that is, the impingement efficiency equals unity.

To estimate the horizontal momentum impacted to the aircraft, visualize the process as that of a water jet whose discharge is equivalent to the rainfall interception rate of 530 kg/sec. The water jet is hitting the 747 at 65 m/sec and loses all its momentum to the plane. What is the force the plane must apply to overcome the jet?

In the horizontal x-direction

$$-F_x = W(-V_o) \tag{5}$$

where W is the mass of water per second and

$-V_o$ is the horizontal velocity of the water jet.

The final velocity of the water after impact is assumed to be zero. Then

$$\begin{aligned} +F_x &= WV_o \\ &= 530 \text{ kg/sec} \times 65 \text{ m/sec} \\ &= 7740 \text{ lbs of force.} \end{aligned}$$

Comparing this number to the maximum thrust of the 747, approximately 180,000 lbs, the momentum of the rain constitutes about 4% to 5% of the plane's maximum thrust. However, in a landing configuration this 4% to 5% of the maximum thrust will be a large percentage of available thrust and could rapidly bleed off airspeed if thrust is not applied. A more quantitative evaluation of this momentum loss effect requires a landing simulation program. Nevertheless, it appears that if undetected the lost momentum could rapidly bleed airspeed and result in putting the aircraft in a low energy state.

The rain momentum calculation was based on assuming that all the rain strikes the plane directly and takes on the plane's momentum. The assumption that all the rain in the path of the aircraft impacts is a fairly good one for high rainfall rates. The mean drop diameter of very heavy rains is large enough such that the drops are not greatly deflected by the airflow around the wing and plane. The trajectories of large drops are nearly straight lines, thus most of the rain that can strike the plane does strike the plane. For low rainfall rates and smaller mean drop diameters, the deflection would be much greater and the impingement efficiency much less.

The assumption that the rain strikes the plane directly and takes on its momentum is an underestimation for drops striking head-on. Any reflections for these drops will be at an angle greater than 90° thus the impact force from the partially elastic collision of these drops is actually greater than accounted for in the momentum calculations. Drops striking the wing or fuselage at an angle less than 90° will suffer reflection at an oblique angle. The force impacted by these drops is less than that accounted for in the momentum calculations. A more detailed analysis of raindrop momentum on an aircraft requires calculation of drop trajectories and an assessment of the effect of drop impacts upon a wing coated with a water film.

The vertical force of rain impact on the aircraft is considerably less. Since the vertical velocity of rain is about 8 m/sec and the mass 530 kg for rain striking the top surface area of the aircraft, the vertical force is

$$F_z = 530 \text{ kg/sec} \times 8 \text{ m/sec}$$
$$= 953 \text{ lbs of force.}$$

This vertical force is less than 20% of the horizontal force and by comparison to the weight of the aircraft would exert a negligible effect on the aircraft performance.

The calculation of rain induced weight and momentum penalties ignored a landing wing configuration using flaps and spoilers which could increase the rain momentum impact with a decreased wing lift. A further deterioration under such conditions would result.

In summary the retarding caused by very heavy rain are:

1. Increased weight of aircraft due to water film on fuselage and wing, could easily be 1% to 2% of landing weight for very heavy rain.

2. Loss of 5% or more of the maximum thrust due to impact momentum of rain. Since only limited additional thrust is available during landing the required thrust may be a very large percentage of the available thrust.

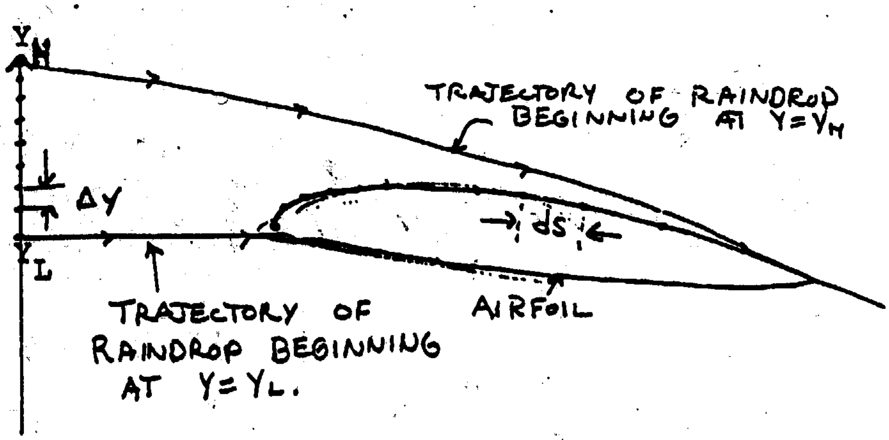
These effects superimpose and could present the pilot with increased stall speed and decreased maneuverability in adverse weather conditions. The effects could become crucial in the presence of wind shear and/or a strong downdraft.

ROUGHNESS OF AIR FOIL

Necessary to evaluating the roughness of an airfoil due to heavy rain is a calculation combining potential flow about the wing with raindrop trajectories in this potential flow field. The potential flow model produces the three-dimensional airflow about an airplane of given configuration. To do this, the potential flow model first calculates the contributions of quadrilaterals covering the airplane surface. The velocity potential at any off-body point can then be found by adding the contributions from all the quadrilaterals. The second task involves calculating the trajectory of a raindrop in this velocity field given its diameter and determining its impact with the airfoil.

We began by modifying an existing (HESS) potential flow model to calculate the flow at off-body points. The task involved examining the code to find how off-body points are specified and how results are output. Due to the complexity of the model, it was decided to calculate an array of off-body point velocities only once. Calculation of raindrop trajectories requires knowing velocities at each drop position as the drop is incrementally tracked through the potential flow field. The air velocity at each drop position is obtained by interpolation from the array of off-body velocities. Since the collection efficiency is dependent upon drop size it is necessary to evaluate the trajectories of various drop sizes characteristic of heavy, severe, and incredible rainfall rates. A summation of mass and momentum for each drop diameter increment can be compared with a calculation done for a volume mean drop diameter. If the differences are small, then further assessments can be done with volume mean drop diameters only.

It is envisioned that the trajectory calculation will proceed in a stepwise manner. It begins along a vertical axis sufficiently far ahead of the wing to avoid any effect on the air flow. (See figure below.) The calculation begins at Y_L



which corresponds to the lowest drops along Y to impact the wing. Interpolation from the potential flow model provides velocities at this point and the trajectory for a short segment is calculated according to the drop trajectory equation,

$$\frac{d\vec{V}_p}{d\tau} = \frac{1}{F_N}\ \frac{1}{V_s}(\vec{V}_a - \vec{V}_p)\frac{B_N R_{N,S}}{B_{N,S} R_N} - \vec{k} \tag{6}$$

where,

$\vec{V}_p$ is non-dimensional drop velocity,

$\vec{V}_a$ is non-dimensional air velocity,

$\vec{k}$ is unit vector in the z direction,

V_s is terminal speed of drop,

τ time increment,

$F_N = V^2/Lg$ Froude Number,

$R_N = \frac{\rho\delta}{\eta}/\vec{V}_a - \vec{V}_p/V$ Reynolds Number,

$B_N = C_D R_N^{\ 2}$ Davies Number,

C_D is particle drag coefficient,

δ is particle dimension,

ρ is air density,

η is air viscosity,

g is gravity,

V is freestream airspeed,

L is a characteristic dimension of the fuselage, and

$R_{N,S} B_{N,S}$ and freestream Reynolds and Davies numbers.

The drop assumes a new position according to this calculation and new drop position velocities are interpolated from the off-body array. The procedure is repeated until either the wing is encountered or passed. The impact momentum and position is retained.

The calculation proceeds by vertical increments until the highest drop to hit the wing has been found. The number and mean diameter of raindrops is known along the Y axis and for purposes of this study is dependent only upon the rainfall rate. This together with the raindrop trajectories leads to an assessment of the collection efficiency as well as the local impingement efficiency for each section of the wing. The momentum contributions can easily be summed to give both horizontal and vertical components.

The problem of calculating collection efficiencies of waterdrops is complicated by the differing response various sized drops have to the airflow around an airplane. The effect raindrop size has on its trajectory is clearly shown in Figures 3, 4, and 5. In Figure 3, 10-μm drops characteristic of clouds flow around a fuselage, note that their trajectories tend to follow streamlines closely. In Figure 4, 100-μm drops characteristic of light rain follow streamlines less closely, and in Figure 5, 1000-μm drops characteristic of heavy rain are hardly deviated by the air stream.

Since the volume mean drop sizes for the high rainfall rates of interest to this study are 1000 μm or larger, collection efficiencies of nearly 100% are expected. In addition, larger drops though less numerous are more efficient in striking the airplane. Larger raindrops also have a higher momentum due to larger mass and terminal velocity. Thus, they constitute the major portion of momentum imparted by rain to an airplane.

The selection of a volume mean radius could lead to an underestimate of the number of drops and momentum impacting the airplane. We can assess the significance of this selection

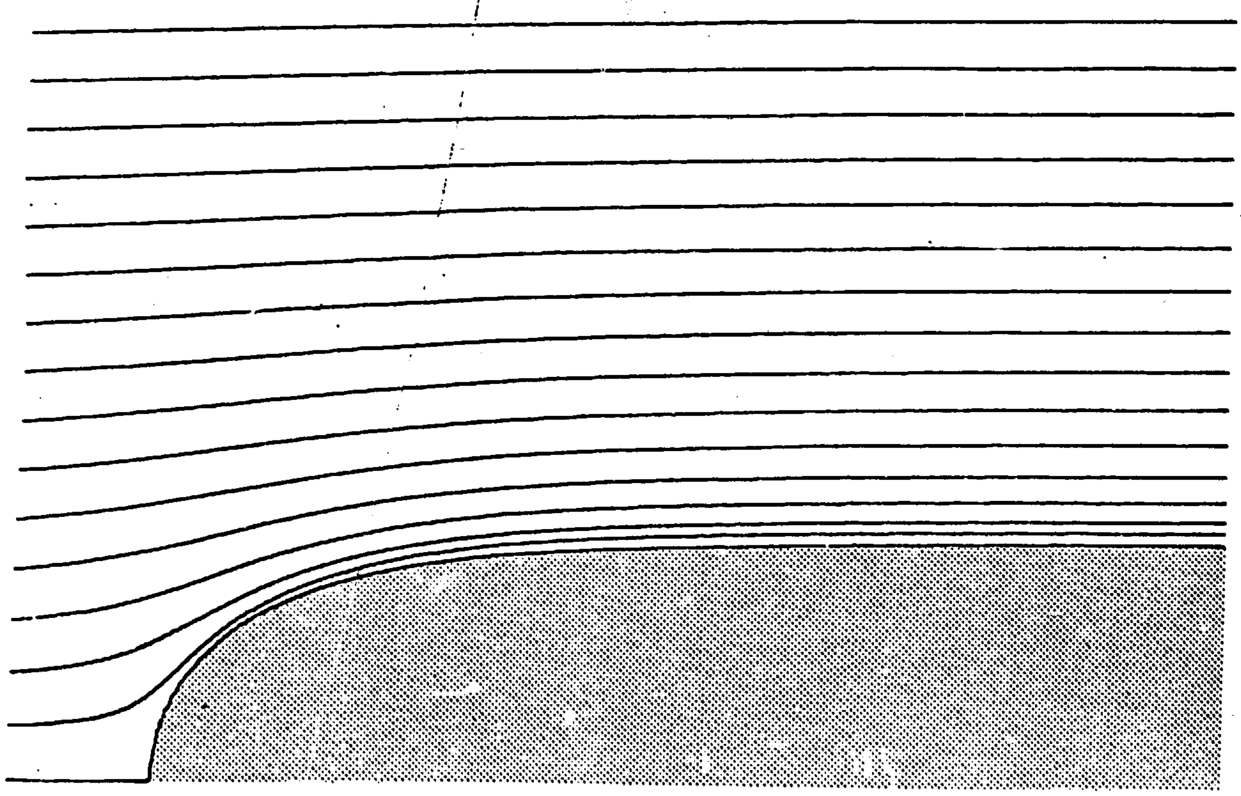


Figure 3. Trajectories of 10 μm Diameter Water Drops in Potential Airflow Around a Single Source Simulating a Fuselage. The trajectories nearly coincide with airflow streamlines.

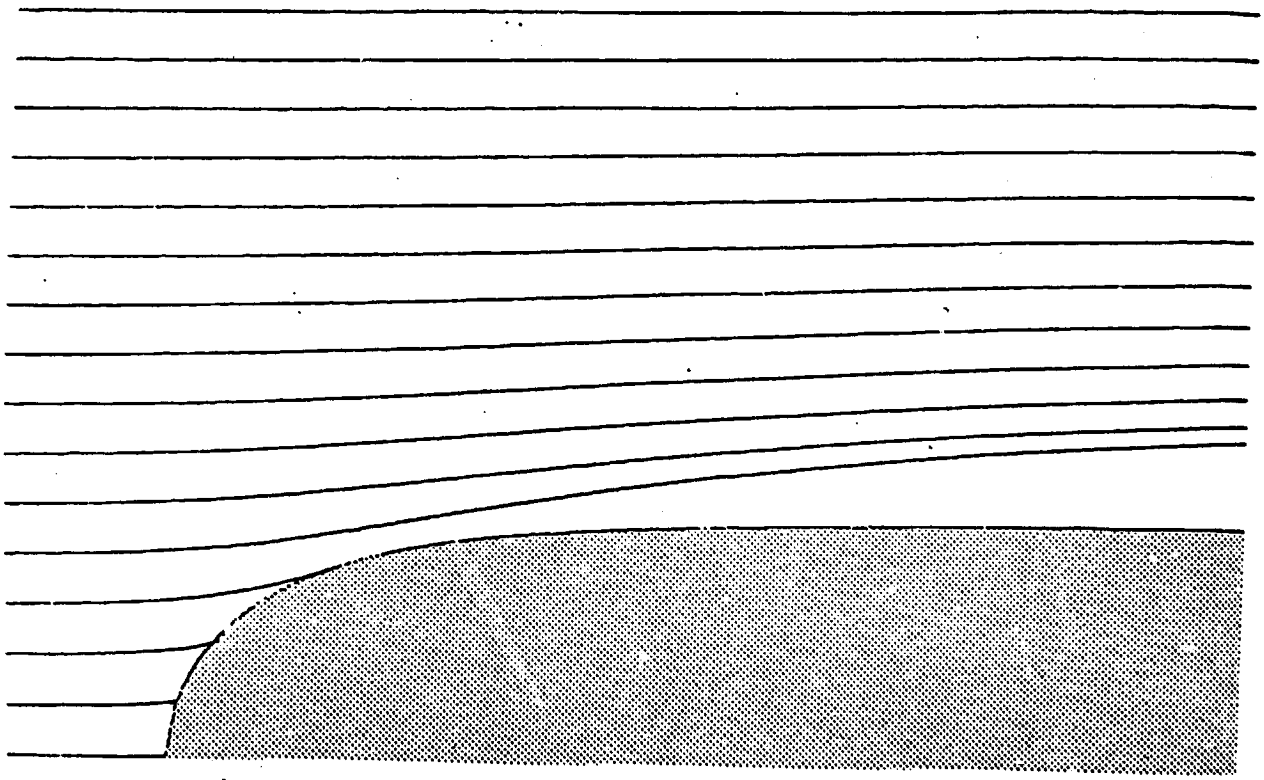


Figure 4. Trajectories of 100 μm Diameter Water Drops through a Potential Flow Field Around a Sincle Point Source.

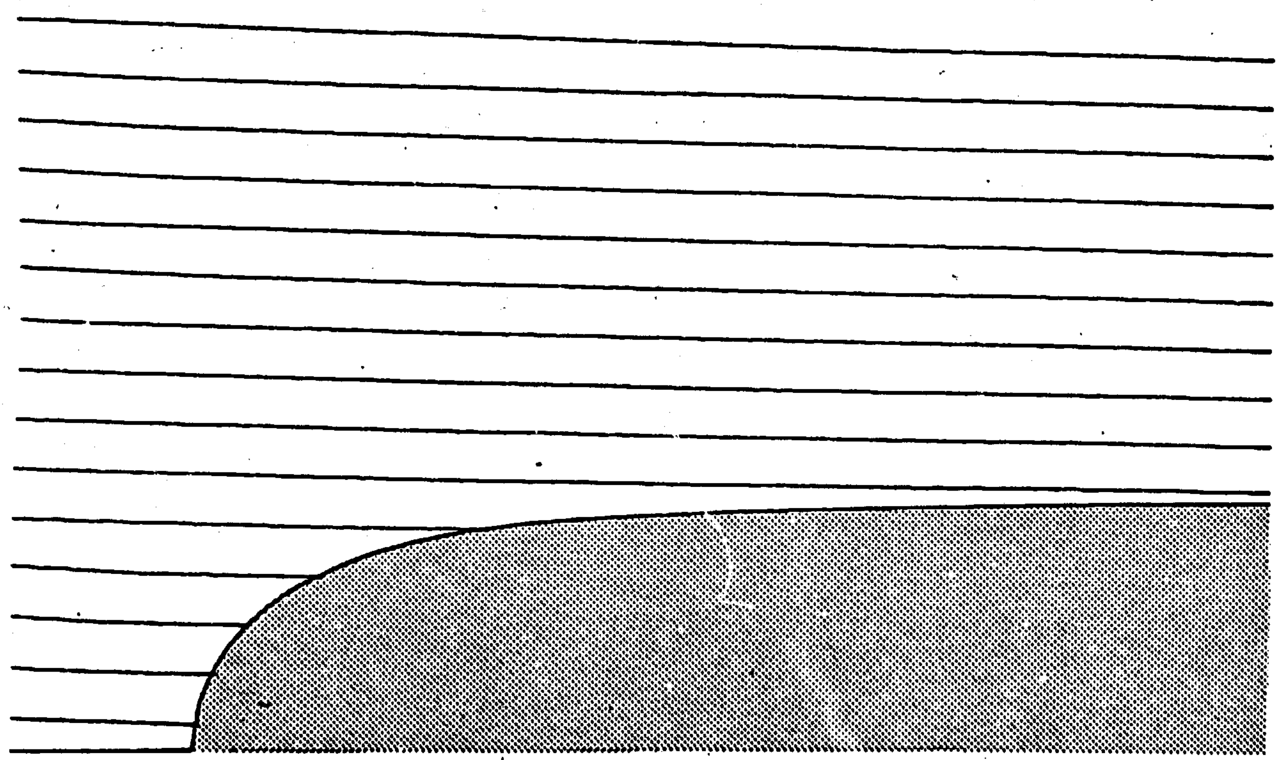


Figure 5. Trajectories of 1000 μm Diameter Water Drop in Potential Airflow Around a Single Point Source. The lift of the trajectories is due to the relatively large terminal velocity of these drops.

by making calculations for both larger and smaller diameters than our volume diameter. A greater initial momentum is possessed by heavier drops due to their higher terminal velocities. This effect may be insignificant when it is remembered that most of the momentum is due to the plane impacting the drops.

It is assumed that the potential flow field is unaffected by heavy rain. This is justifiable since even an incredible rain of 1000 mm/hr constitutes no more than 2 percent of the air volume. An exceptionally heavy or severe rain constitutes an even smaller portion (approximately one percent) of the air volume.

Figure 6 shows the steps leading to assessing the penalties of heavy rain. Figure 7 shows forces on a plane in flight and how they are affected in heavy rain.

The velocity fields were derived from the Hess potential flow model for a wing body. The configuration of the wing body is shown in Figure 8 along with the cross section along which the velocities were calculated. Examples of vertical and horizontal velocities about a wing in potential flow are shown in Figures 9A and 9B.

A computer program for calculating a raindrop's trajectory was written. The program can access off-body velocities created by the Hess program or provide velocities for a potential flow about a single source. In either case, u and w velocities are interpolated to the drop position by an interpolation subroutine. A new drop position is predicted from

$$\frac{du_d}{dt} = \frac{C_D R_e}{24k} (\bar{U}_d - \bar{U}_a) \quad \text{where} \quad R_e = \frac{D_{DROP} \rho_{air} \left[\bar{U}_d - \bar{U}_a\right] u}{\mu} \qquad (7)$$

$$k = \frac{\rho_w D_{DROP} u}{9 \mu L}$$

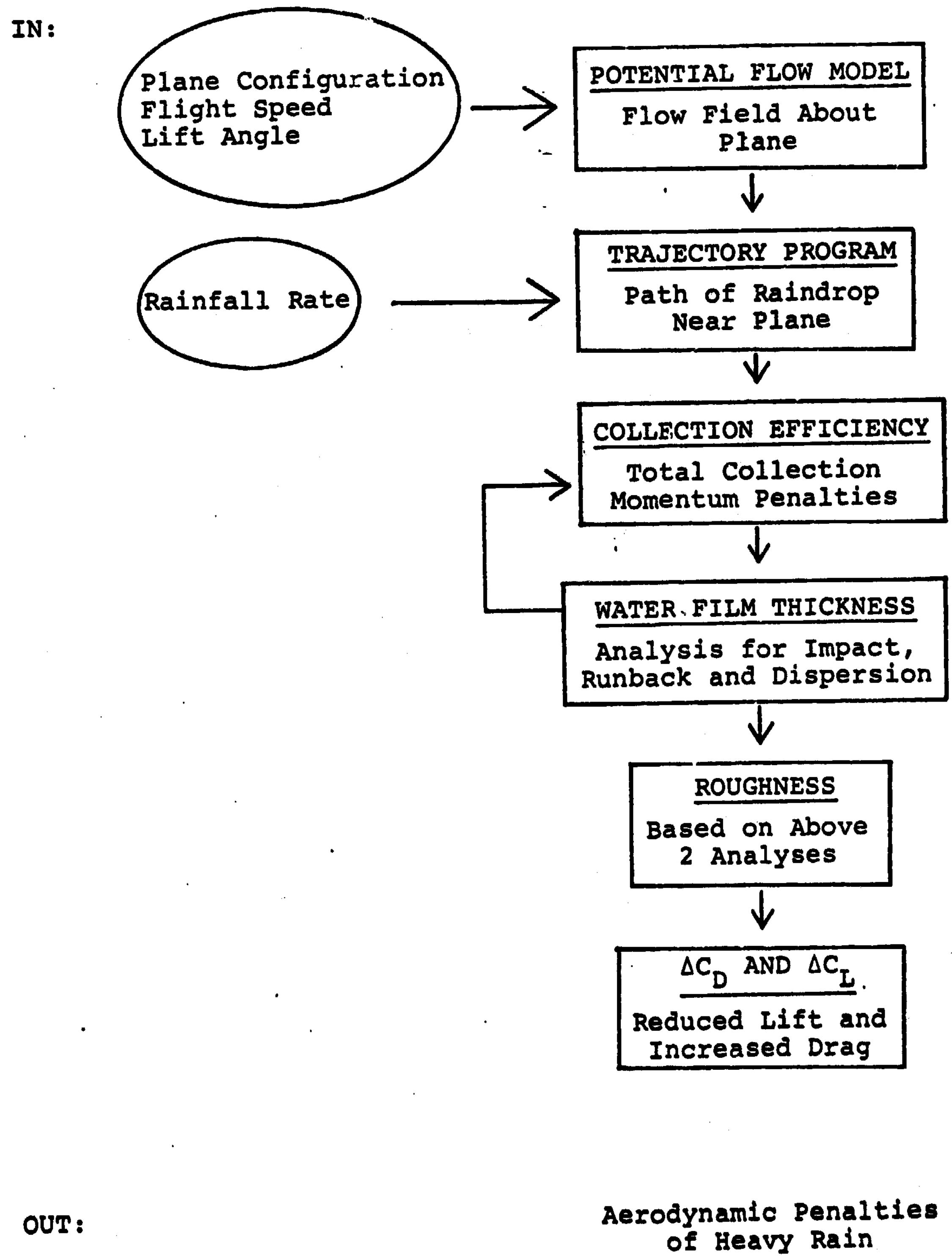
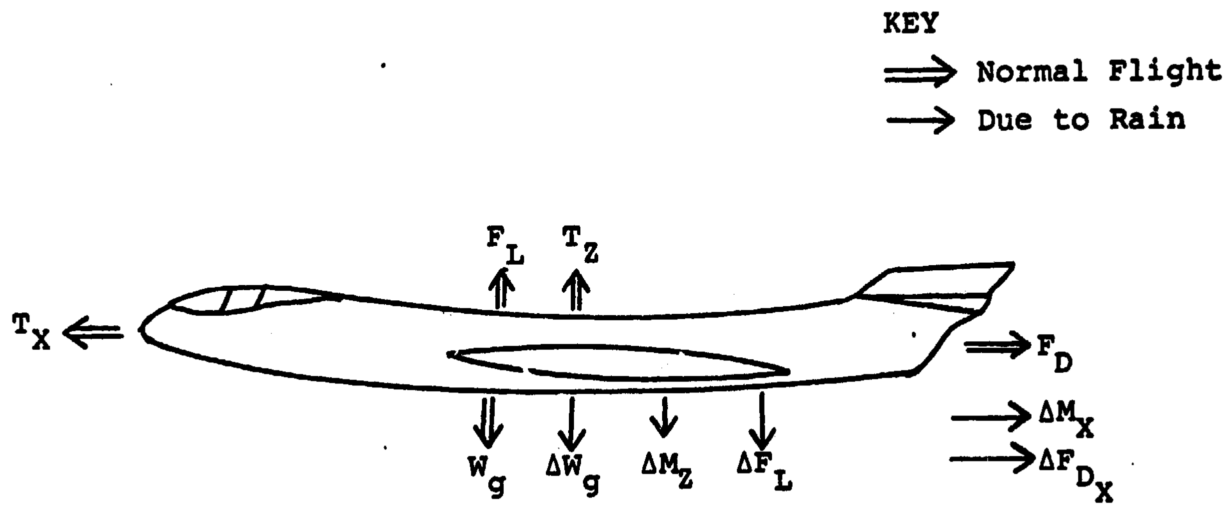


Figure 6. Steps to Evaluating the Penalties of Heavy Rain



I. Forces in Normal Flight

T_X - Thrust in X direction
T_Z - Thrust in Z direction
F_L - Lift force
F_D - Drag force
W_g - Plane weight

$$Z = T_Z + F_L - W_g = \frac{W}{g} a_z$$

$$X = T_X - F_D = \frac{W}{g} a_x$$

II. Forces Due to Heavy Rain

ΔM_X - Rain momentum in X direction
ΔM_Z - Rain momentum in Z direction
ΔF_L - Lift loss due to rain
ΔF_D - Increase in drag due to rain
ΔW_g - Water film weight on plane

$$\Delta Z = \Delta C_{L\rho e} V_a^2 + \Delta M_Z + \Delta W_g$$

$$\Delta X = \Delta C_{D\rho e} V_a^2 + \Delta M_X$$

Figure 7. Forces of Important During Heavy Rain

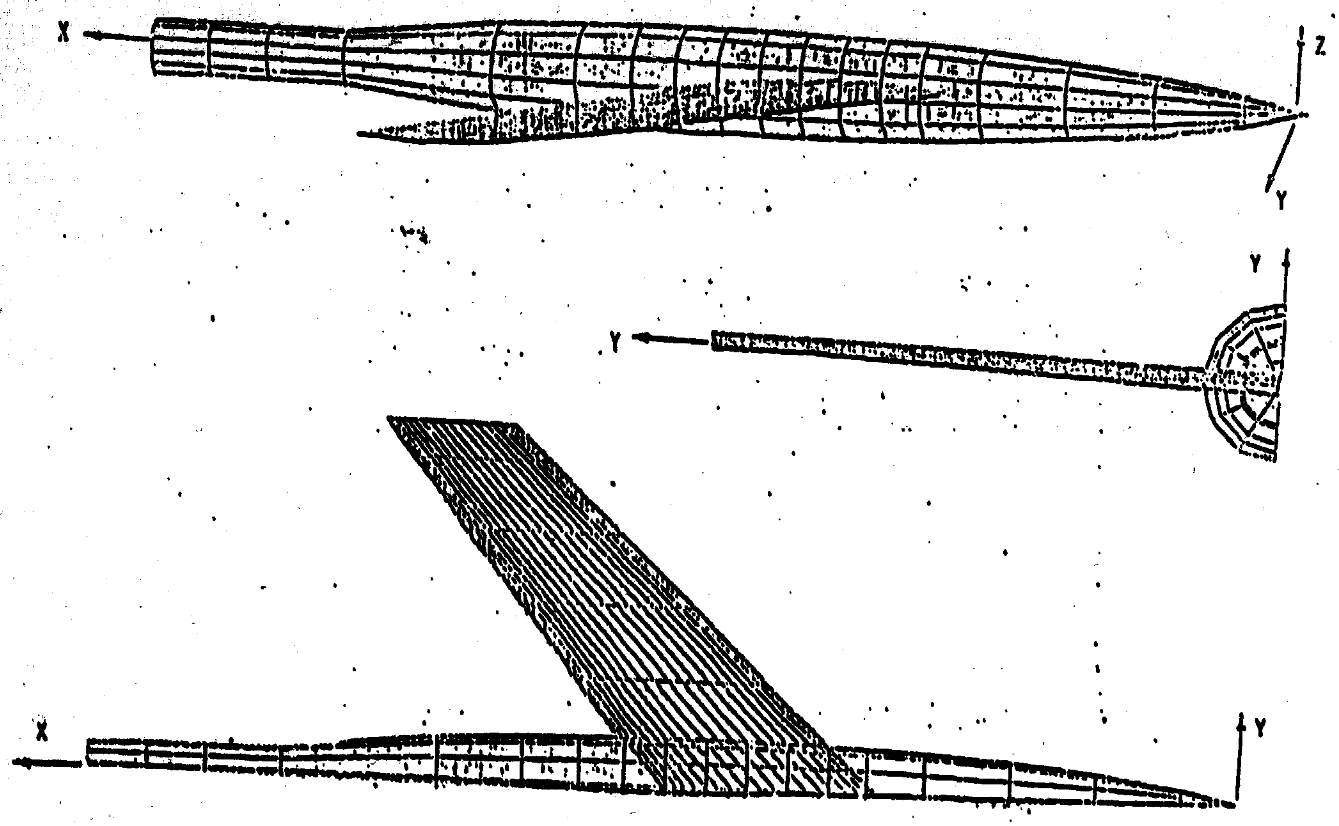


Figure 8. Wing-Body Configuration used to Generate Off-Body Velocities Shown in Figure 9A and 9B

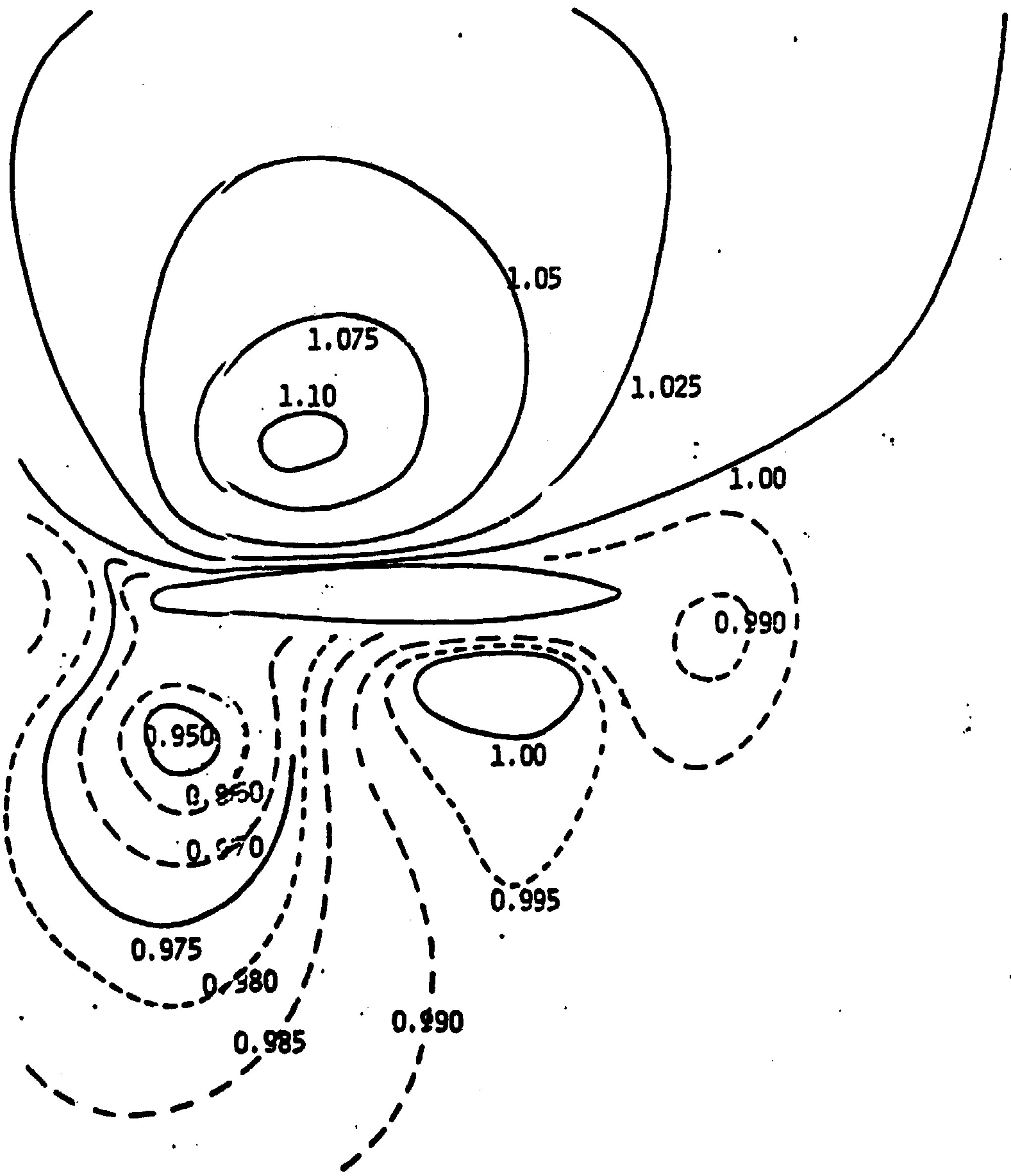


Figure 9A. Horizontal Velocities Induced by a Wing Body in Potential Flow. Numbers indicate the fractional part of the free speed velocity. (~65 m/sec) attack angle 4°

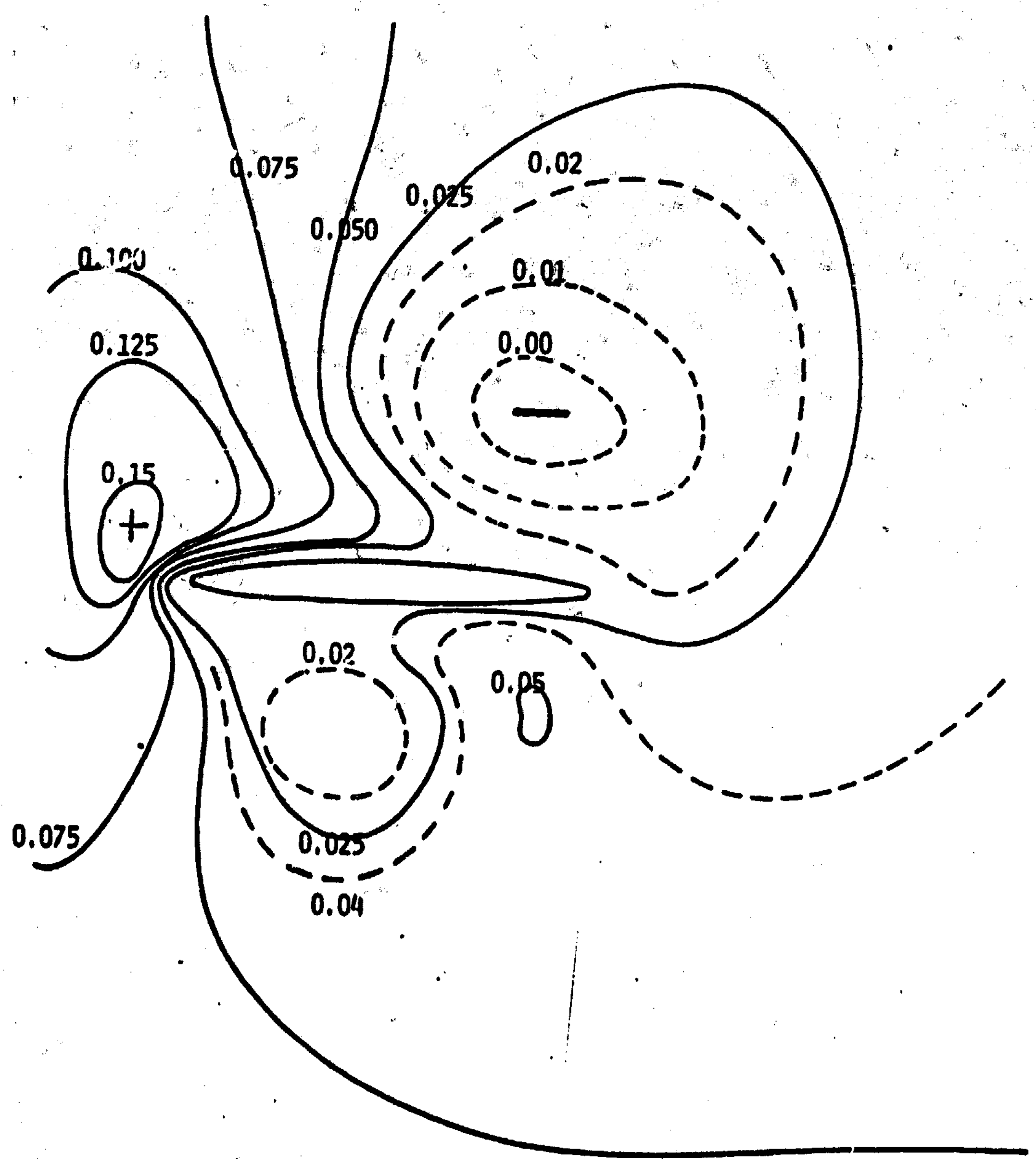


Figure 9B. Vertical Motion Field About a Wing in Potential Flow. The numbers are the decimal part of the free air speed (65 m/sec). attack angle 4°

Drag Coefficient:

$$C_d = \frac{24}{R_e}\left[1 + 0.15R_e^{0.687}\right]$$

except if $R_e > 200$

$$\ln R_e = a_{20} + a_{21} \ln X_2 + a_{22}(\ln X_2)^2 + a_{23}(\ln X_2)^3 \quad X_2 = C_d R_e^2$$

$a_{20} = -0.236534 \times 10^1$, $a_{21} = +0.767787$, $a_{22} = +0.535826 \times 10^{-2}$

$a_{23} = -0.763554 \times 10^{-3}$

$\bar{U}_d$	- non-dimensional drop velocity	ρair	- air density
$\bar{U}_a$	- non-dimensional air velocity	ρ_w	- water density
C_d	- drag coefficient	u	- free stream velocity
R_e	- Reynolds number	μ	- air viscosity
k	- inertial parameter	L	- dimension of fuselage or wing
D_{DROP}	- drop diameter		

which gives the change in the drop's velocity due to the air flow about a wing or fuselage. Integrating Equation 7 leads to a new drop position,

$$du_d = \frac{C_D R_e (U_d - U_a)}{24} \left(\frac{dt}{k}\right)$$

$$u_d = U_d + du_d$$

$$x_d = x_d + U_d dt$$

position. The process is now repeated for the new position and continues until either the wing is impacted or the drop passes by the wing. The time step Δt will nominally be 0.01 sec but is designed to shorten if large accelerations of the drop are occurring. A small drop undergoes large accelerations in the vicinity of the wing.

In Figures 10, 11, and 12 results of trajectory calculations are shown. The ambient velocity field is for potential flow about a single source. Velocity components are:

$$V_x = 1 + x/4q^3$$

$$V_z = z/4q^3$$

$$\text{where } q^2 = x^2 + z^2$$

Figure 10 shows trajectories of large raindrops (rad = 0.2 cm) characteristic of severe or indredible rainfall rates. The trajectories of such drops are nearly straight lines indicating that the inertia of large drops is large enough to prevent deflection by wing or fuselage airflow. Figure 11 shows trajectories of medium sized (rad = 0.02 cm) raindrops. Trajectories are deflected somewhat by an obstacle's airflow. Figure 12 shows trajectories of small drops (rad = 0.001 cm) which are characteristic of cloud droplets. The trajectories of small drops follow the airflow streamlines very closely.

The most important results from the trajectory calculations is the nearly straight line trajectories of large drops. Collection efficiencies for small drops such as those making up clouds have been extensively calculated and are known to be small. Figure 12 confirms these calculations by showing the large deflections of small drops which makes their reaching the wing difficult. Large drops, such as might be encountered in severe or incredible rains have enormously greater inertias and are barely deflected from straight-line paths. Therefore, the collection efficiency for very heavy rain is nearly 100 percent and the amount of collection is most dependent upon the exposed cross-section presented to the rain. The calculation for wing collection (amount of rain intercepted by wing section) may then be simplified for very heavy rains and consist only of trajectories whose slope is the ratio of drop terminal velocity to aircraft speed and their intersection with the wing.

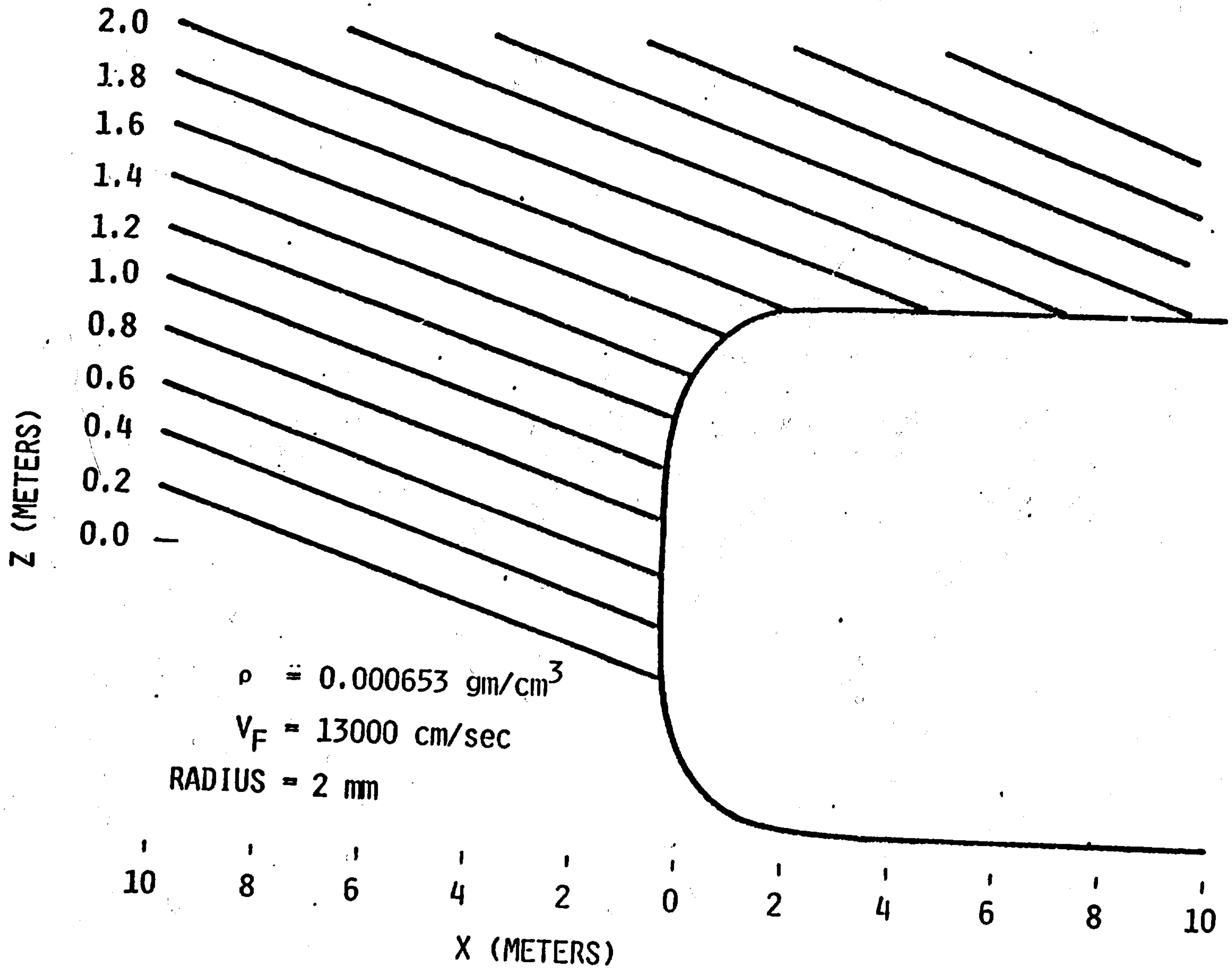


Figure 10. Trajectories of 2 mm Radius Drops in Potential Flow About a 10 m Radius Fuselage. Free airspeed is 130 m/sec.

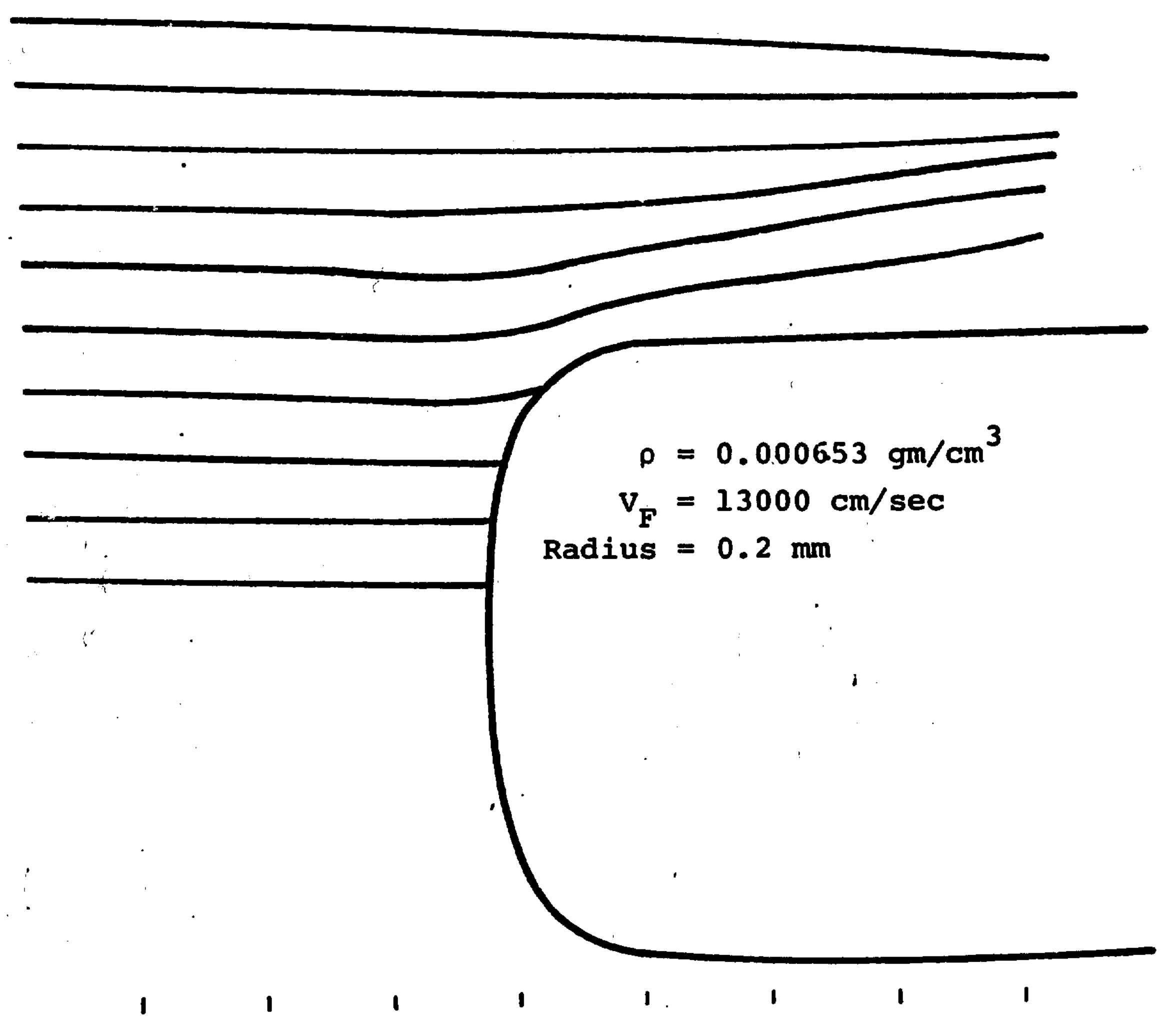


Figure 11. Trajecotries of 200 μm Radius Drops in Potential Flow About a .5m Radius Fuselage. Free airspeed is 130 m/sec.

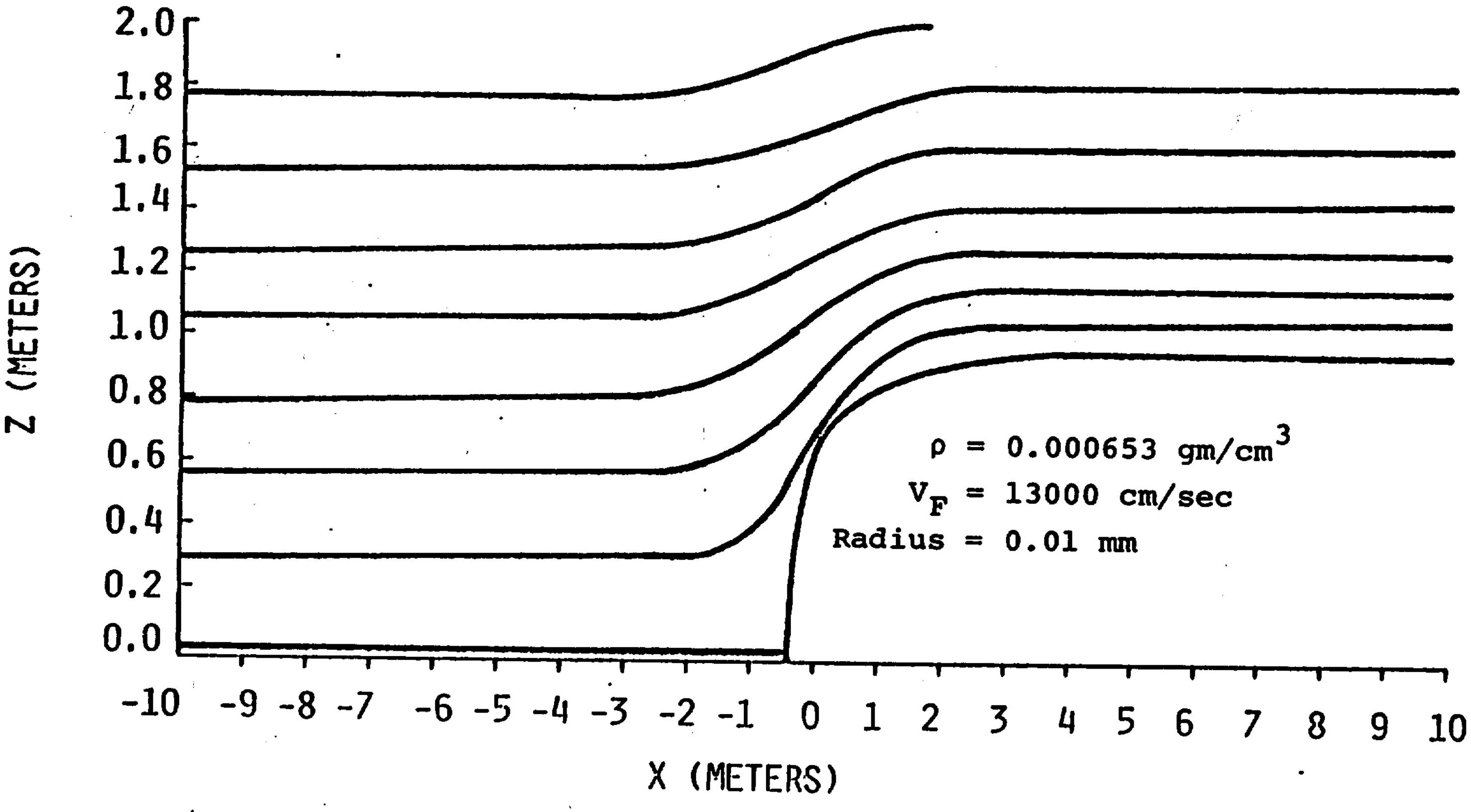


Figure 12. Trajectories of 10 μm Radius Droplets in Potential Flow About a 1.5 m Radius Fuselage. Free airspeed is 130 m/sec.

REFERENCES

Bergrun, N. R., 1951, "An Empirically Derived Basis for Calculating the Area, Rate, and Distribution of Water-Drop Impingement on Airfoils," NACA RN 1107, 1079-1099.

Berry, E. X. and M. R. Pranger, 1974, "Equations for Calculating the Terminal Velocity of Water Drops," J. Appl. Meteor., 13, 108-113.

Blanchard, D. C. and A. T. Spencer, 1970, "Experiments of the Generation of Raindrop-Size Distributions by Drop Breakup," J. Appl. Meteor., 27, 101-108.

Bodtmann, W. F. and C. L. Ruthnoff, 1976, "The Measurement of 1 Minute Rain Rates from Weighing Raingage Recordings," J. Appl. Meteor., 15, 1160-1166.

Hershfield, D. M., 1972, "Estimating the Extreme-Value 1 Minute Rainfall," J. Appl. Meteor., 11, 936-940.

Jones, D. M. A. and A. L. Sims, 1978, "Climatology of Instantaneous Rainfall Rates, J. Appl. Meteor., 17, 1135-1140.

Markowitz, A. M., 1976, "Raindrop Size Distribution Expressions," J. Appl. Meteor., 15, 1029-1031.

Marshall, J. S. and W. McK. Palmer, 1948, "The Distribution of Raindrops with Size., J. Meteor., 5, 165-166.

Merceret, F. J., 1974, "On the Size Distribution of Raindrops in Hurricane Ginger," Mon. Wea. Rev., 102, 714-716.

Merceret, F. J., 1975, "Relating Rainfall Rate to the Slope of Raindrop Size Spectra," J. Appl. Meteor., 14, 259-260.

Noll, K. E. and M. J. Pilat, 1970, "Inertial Impaction of Particles upon Rectangular Bodies," Journal of Colloid and Interface Science, 33, 197-207.

Norment, H. G., 1976, "Additional Studies of the Effects of Airplane Flowfields on Hydrometeor Concentration Measurements," Rep. AFGL-TR-76-0187, Air Force Geophysics Laboratory, Hanscom AFB, Mass., 1-56, AD-A032 311.

Sims, A. L. and D. M. A. Jones, 1975, "Frequencies of Short-Period Rainfall Rates Along Lines," J. Appl. Meteor., 14, 170-174.

Smith, R. L., 1978, "Closed-Form Equations for the Lift, Drag, and Pitching Moment Coefficients of Airfoil Sections in Subsonic Flow," NASA Technical Memorandum 78942, 1-55, N78-29068.

Streeter, V. L., 1966, Fluid Mechanics, McGraw-Hill, New York, 705 pgs.

Walsh, M. J., 1977, "Comment on 'Drag Coefficient of Spheres in Continuum and Rarefied Flows'," AIAA Journal, 14, 893-894.